Micro-Process of the Tilting Motion of Ground and Structures

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by

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(Communicated by Prof. E. Nishimura)

Abstract

The continuous and precise observations with many sets of high sensitive, versatile tiltgraph were made to study the micro-process of tilting motion of ground and structure in cases of ground-sinking by pumping up of underground water, deformation of tunnel by earth-pressure, unequal sinking of structure of railway station, and deformation of dam by water load. It is generally concluded that the phenomena are unexpectedly complex in all cases, but this sort of observation is certainly useful to solve the nature of deformation of ground and structure, and profitable to make a counter-plan to protect them from disasters.

1. Introduction

In resent years various problems on ground-sinking at the industrial city, unequal sinking of the ground under the large and heavy structure, breaking of large dams by extraordinary heavy rainfall and earthquake, dangerous deformation of tunnel of railway and mine, and other allied phenomena have been becoming more and more serious for our modern living. Certainly these problems are earnestly studied by many people from the standpoints of civil and architectural engineering, and really many suitable and valuable counter-plans for these damages have been adopted and serviceable to a certain degree for prevention of such disasters. But, essentially considering the nature of these phenomena, it has a very complex character and, for solving perfectly the problem, it needs an intimate cooperation of various fields of science. In detail speaking, technical knowledge of civil and architectural engineering must necessarily be supplemented by those of geodesy, seismology, meteorology, hydrology, geology, and other allied sciences.

As one branch of synthetic study on the above mentioned disasters, the geophysical observation of micro-tilting motion of ground and structure with a high sensitive, versatile tiltmeter of automatic recording has been recently operated by the members of Disaster Prevention Research Institute of Kyoto University at various places for several cases. The aim of this research is to observe the micro-process of tilting motion of ground and structure and, from it, to clarify the nature of their deformation, and further to be serviceable for useful counter-plans for prevention of the disaster in cooperation with several of the technical science.

In the following, an explanation of tiltmeter used in the present study, and the observed results in various cases of deformation of ground and structure, are represented in sequence.

2. Function of P_1-Tiltgraph

The tiltgraph used in the present research is named "P_1-Tiltgraph" designed by personnel of the Disaster Prevention Research Institute, and its structure and function are as follows:

The type of P_1-Tiltgraph is of horizontal pendulums of Zöllner suspension. Two pendulums are orthogonally placed in one metal or wooden box, and recording equipment with one electric lamp of light source is also contained in one box as seen in Fig. 1. The dimension of the boxes of pendulums and recorder are $35\times40\times25$ in cm and $26\times40\times35$ in cm respectively, weighing each nearly 11 kg. In observation, two boxes are tightly joined as one set, as seen in Fig. 1, and the cups of levelling screw of circular stand of horizontal pendulum are directly set up on the stone or concrete block by removing the bot-

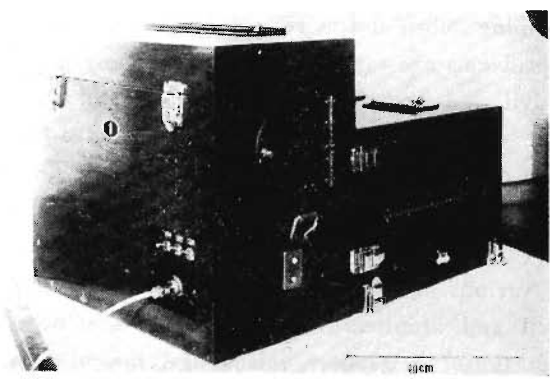


Fig. 1.

tom sheet of the box.

The part of horizontal pendulum is in detail shown in Fig. 2. The arm of pendulum, suspension wire and vertical rod for suspension are all made of super-invar alloy, and the bob of pendulum is made of pure copper and covered with gold. The free oscillation of pendulum is suitably damped by an electromagnetic damper with permanent magnet, because the present tiltgraph is usually used for observation of micro-tilting motions of ground and structure where short periodic vibrations of artificial origin are predominantly observed. The dimension of various parts of the pendulum are as follows:

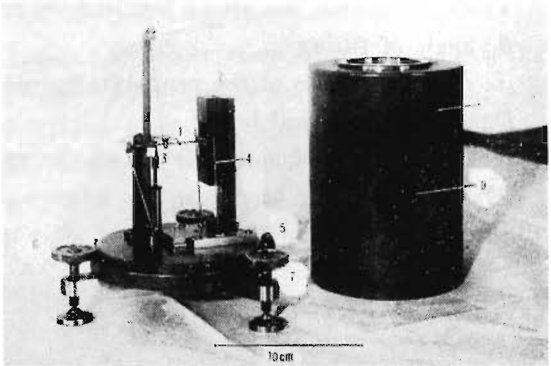


Fig. 2. Horizontal pendulum of P_1-tiltgraph.
1: arm of pendulum 2: magnetic damper 3: reflecting mirror 4: stopper 5: controlling screw for damper 6: controlling screw for pendulum-period 7: controlling screw for zero-point adjustment 9: optical window of metallic cover

The equivalent length of simple pendulum (l) :	3.8 cm
The length of vertical rod for suspension :	14.0 cm
The diameter of suspension wire (2r) :	30 μ
The mean length of suspension wires :	6.6 cm
The weight of bob :	13.4 gr
The modulus of rigidity of suspension wire :	5×10^{11} dyne/cm
The optical length of recording (D) :	30 cm

Sensitivity of P_1-Tiltgraph is calculated by the following formulae neglecting torsional effect of the suspension wire.

$$T=2\pi\sqrt{\frac{l}{gi}}$$

$$\theta=i\varphi$$

$$d=2D\varphi$$

where

T: free period of pendulum without damping

l: equivalent length of simple pendulum

g: gravity acceleration

i : angle between the plumb line and the rotation axis of the pendulum
θ : angle of tilting
φ : deflection angle of the pendulum caused by θ-tilting
D : Length of optical lever
d : displacement of optical image on the recording paper

From the above relations, the relation between the sensitivity of tiltgraph (d/θ) and the free period of T is represented as

$$\frac{d}{\theta}=\left(\frac{gD}{2l\pi^2}\right)T$$

In the present case, the period of pendulum (T) for the sensitivity of 1 cm/1″ is calculated by the above relation by putting the following numerical values for coefficients. Namely, in case of $l=3.8$ cm, $D=30$ cm, $d=1$ cm, $\theta=1''=0.4848\times10^{-5}$, $g=980$ cm/sec^2

$T=22.9$ sec for the sensitivity of 1 cm/1″

The general aspect of the relation between the sensitivity of P_1-Tiltgraph and the period of pendulum are shown in Fig. 3, where the sensitivity is represented in θ''/1 mm meaning the displacement of the optical image on the recording paper is equivalent to the amount of ground-tilting in the seconds of angle, and we can easily observe the small amount of tilting of 0.1″ by this instrument. Moreover, in case of need, the sensitivity of instrument can be raised up to the order of magnitude of 0.01″/mm by lengthening both the optical distance in recording and the period of pendulum. It is to be remarked that the value of sensitivity in this Figure is applicable to the tilting motion of a long period, namely larger than that of one minute in the present case.

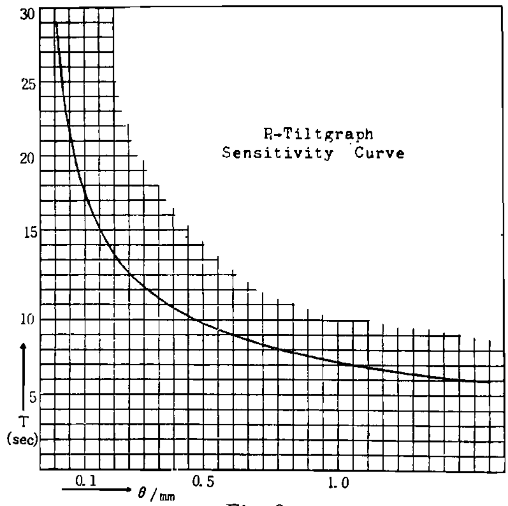


Fig. 3.

In the present observation, the pendulum must necessarily be damped by a suitable method. Because the observation is usually made at the place where the ground is largely disturbed by traffic, vibration of machine and motor, oscillation caused by strong wind, and other various artificial causes. The present tiltgraph is equipped with an electromagnetic damper as seen in Fig. 2, and its effects are shown in Fig. 4. In

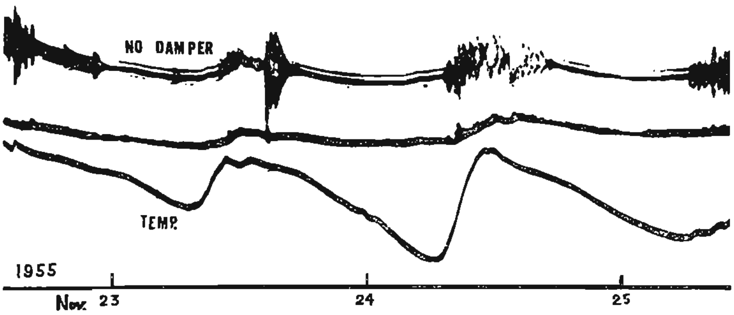


Fig. 4.

Fig. 4, buckling motion of building by sunshine is recorded at an underground room of building with two tiltgraphs of the same type with or without the damper. A tiltgram recorded with the tiltgraph having a damper showed a smoother curve compared with that of tiltgraph without it due to being disturbed by restless motions in day time caused by the artificial excitations.

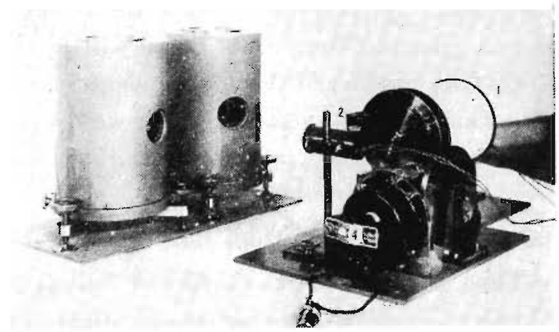


Fig. 5. Recording apparatus.
1 : recording drum 2 electric lamp
4 : synchronous motor

The recording apparatus consists of three parts; an electric lamp, rotation drum and the synchronous electric motor, as seen in Fig. 5. The rotation speed of recording drum can easily be changed for duration of 6 hours, 24 hours, 42 hours and 7 days per one revolution by control of the speed of motor and combination of the screws. The synchronous electric motor is driven by electric supply of an alternating current of 100 V.

Thus the present tiltgraph of P_1-type is easily manipulated by one man and effectively used at any place of high ground noise for observation of the micro-tilting motion of the ground and any structure. In the following some cases of its practical application and their results will be described.

3. Tilting Motion of the Ground Caused by Level Change of Underground Water

Recently the problem of ground sinking in industrial cities and the gas-oil field has become very serious. For example, the down-town of Tokyo, the industrial quarters of Osaka and Amagasaki, and gas-field area of Niigata have come to suffer great damages by ground-sinking of large amount caused by large consumption of the underground water and oilgas. It is a pressing need to clarify the mechanism of this sort of ground-sinking and establish effective counter-plans to prevent the progress of disaster. Along this line we have been studying the behavior of the ground with P_1-Tiltgraph in case of pumping and pouring the underground water from and into the water well at Osaka and Amagasaki since 1951. In the present article the recent results observed at grounds of two industrial factories in Osaka will be reported, they being Takeda Drugs Corporation and Osaka Gas Company, selected to observe the micro-tilting motion of the ground near the well of plant water with P_1-Tiltgraph in case of pumping (discharge) and pouring (recharge) of the water from and into its well.

(a) Case of Takeda Drugs Corporation

The ground of Osaka Factory of Takeda Drugs Corporation is situated at the northern part of Osaka alluvial plain, and, in the present observation, four sets of P_1-Tiltgragh were used to observe the effect of recharge of water into a well upon the micro-tilting motion of nearby ground, the depth of well being 72 m and the level of water 20 m deep below the ground surface. The positions of the well (W_1) and four tiltgraphs (No. 1, 2, 3 and 4) are shown in Fig. 6. The observation period was February 29-March 17, 1956. Of the well concerned, the

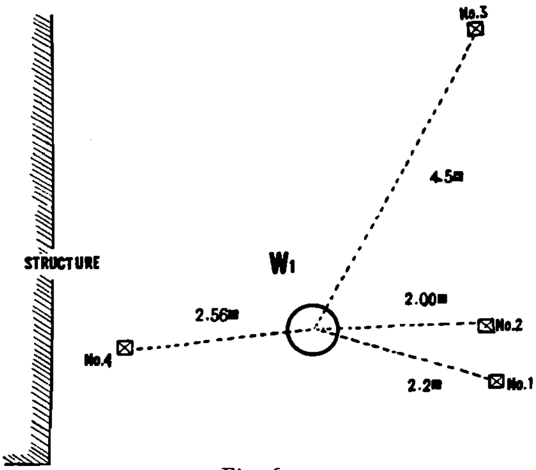


Fig. 6.

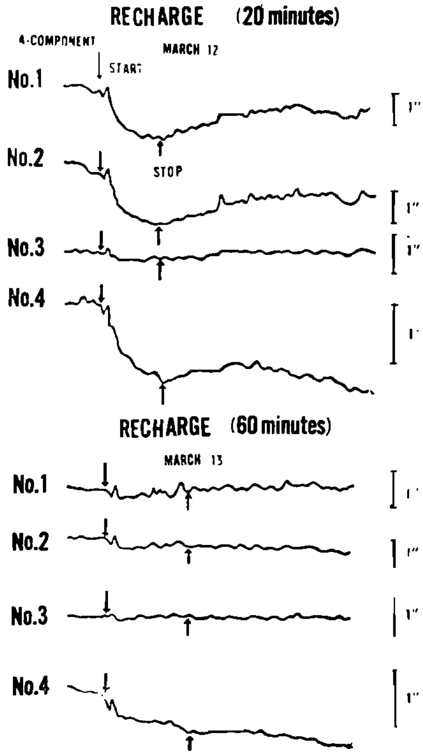


Fig. 7. Tiltgrams obtained at Takeda.

recharge of water of usual temperature was continuously, in usual case, operated in daytime at a rate of nearly 9.6 tons per hour, and stopped during night. In the present observation, two kinds of measurement were operated. Namely, one is the study of recharge effect upon ground-tilting in short duration within one hour ; and the other is that in a long duration of several days. Concerning the short period measurement, the following procedure was adopted. First, the recharge of water was on purpose stopped two hours before the commencement of observation, and then an observation with four sets of tiltgraph was operated in the condition of continuous recharge of water during the period within one hour, and continued to a period of some hours after the stoppage of recharge for the purpose of examining the process of recovery of micro-ground-deformation. In this observation, the period of recharge adopted was 3, 5, 10, 20, 25, 30 and 60 minutes respectively, and two examples of tiltgrams in case of 20 minutes and 60 minutes are shown in Fig. 7. In the Figure, all curves are the tiltgrams showing the ground-tilting in radial direction pointing to the well, and the curves of tangential component are omitted because of no concern in case of the recharge. The downward change of curve shows the ground-tilting downward in the direction pointing to the well seen from the point of tiltgraph.

As seen in Fig. 7, the ground nearby the well once sinks and then rises immediately after commencement of the recharge, and then gradually sinks again and continues its sinking motion during the period of recharge. This sinking motion is stopped when the recharge is stopped, and after it, the ground generally recovers to the initial state. But, in this case, it must be remarked that the words "sink" and "rise" of the ground nearby the well are conventionally used in the meaning of type of ground-deformation at the well relative to the neighbouring ground because the present observation is operated only with the tiltgraph. A simultaneous observation with other instruments of different type, should be supplemented to study the whole motions of the ground. It must be here noticed that the modes of "sink" and "rise" are conveniently used in the sense above mentioned in all paragraphs of the present article. These behaviors of ground are nearly the same for all observation of different periods of recharge duration (3 min-60 min) and for all points but No. 4. The point No. 4 is situated close by a tall wooden building with iron skelton, and the effect of bucklng motion of building by sunshine and others, and of sinking motion of building itself by charge of underground water, presumably affected the behavior of ground deformation at the point No. 4. This curious phenomenon of ground-sinking nearby the recharging well, during the process of recharge of short duration within one hour, is contradictory to the common knowledge of recharge behavior. This problem is not, at present, fully solved, but the following conditions will possibly be presumed to have connection with this curious phenomenon. One is a fact that, in process of this experiment, the pumping the underground water up for industrial purpose is continuously operated at another well 60 m from the recharge well concerned. Another interpretation is also probable that it is a peculiar phenomenon to the ground concerned, because the ground nearby the well in another observation at Osaka Gas Company is normally raised by the recharge of water as is described in the following paragraph. Further, another consideration is here proposed that it depends upon the shortness of time interval of recharge, and really, in case of recharge of long durations, the ground is once sunk and then raised by the continuous recharge in long time intervals as shown in Fig. 8.

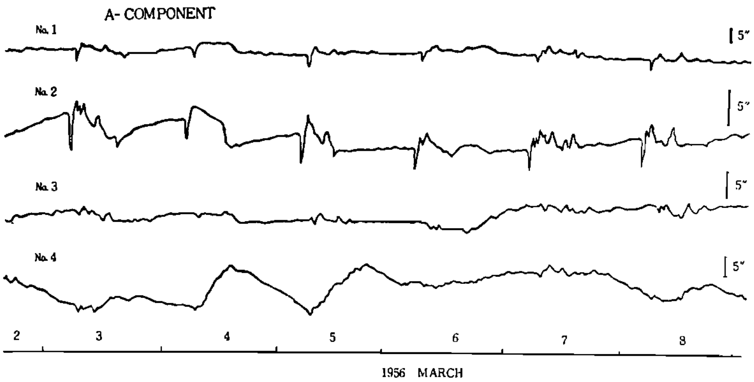


Fig. 8. Ground-tilting observed at Takeda.

Recorded curves of the tiltgraph in the direction of the well in long intervals of several days are shown in Fig. 8. In this case, the recharge of water is continuously operated in rate nearly 9.6 tons per hour daily from 4 to 13 o'clock. As seen in the Figure, the ground at the stations No. 2 and No. 3, especially at No. 2, shows a rapid sinking immediately after commencement of the recharge, and then reverses its tilting motion in raising up itself to the highest position over the neutral one in the time of about 2 hours after commencement of the recharge.

After stoppage of the recharge the ground begins again a gradual sinking and settles itself to a neutral position in about 2 hours. Concerning the ground at No. 4, it is strongly affected by the buckling and sinking motion of a close building, showing the so-called diurnal ground-tilting usually observed at any place. It is to be mentioned that the behavior of ground effected by water-recharge, is nearly the same for all points and days concerned, but their amounts and modes of tilting, as clearly seen in the Figure, are largely affected by soil conditions which properties are depending on meteorological changes and hysteresis such as the rainfall, sunshine and the like. It is also strongly modified by condition of the underground water level in neighbourhood which fluctuates by the daily amount of use of industrial water.

(b) Case of Osaka Gas Company

The tiltmetric observation was made at the ground of Torishima Factory of Osaka Gas Company during a period of March 23–April 4, 1956. First the ground-tilting caused by the pumping of water was studied when the rate of pumping and time interval were nearly 140 tons per hour and several hours respectively. The positions of four sets of tiltgraph and the well (W_2) are shown in Fig. 9. But, in this case, the downward tilting in the direction of water tank (pond) of $12\times16\times1.7$ m^3 were predominantly observed, the amount and direction of ground-tilting at 4 points being shown in a vector form in the Figure. These large tiltings were certainly due to a bending motion of the ground caused by an increase of water load in the water tank into which the whole amount of pumped water was poured. For this reason, the effect of pumping water upon the ground deformation could not be ascertained in this experiment.

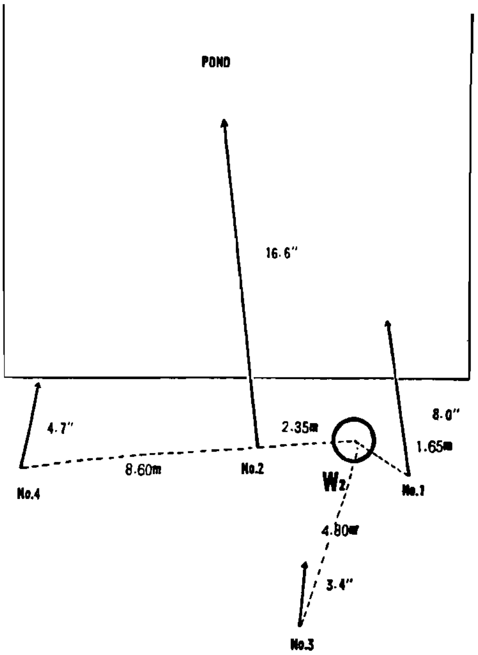


Fig. 9.

Next, for the purpose of observation on effect of recharge, another well (W_1) was adopted, the positions of four sets of tiltgraph and the well (W_1) being shown in Fig. 10. In this case, the rate of recharge was nearly 11.8 tons per hour and the temperature of recharging water was a high industrial one of 60°C. In observation, as in case of Takeda Drugs Corporation, after the stoppage of recharge in an interval of 40–60 minutes before commencement of the experimental recharge and continued during 30–40 minutes intervals, and then the stoppage of recharge operated in an interval of 1 hour. One example of tiltgram obtained in this experiment is shown in Fig. 11. The A-component means a tiltgram curve in the direction pointing to the well from the respective point of the tiltgraphs and the upward change shows a rise of the ground at the well. In this case, it is clearly ascertained that the ground at the well is raised by the effect of recharge of water into the well, and its effect extends to the ground of a considerably long distance from the well.

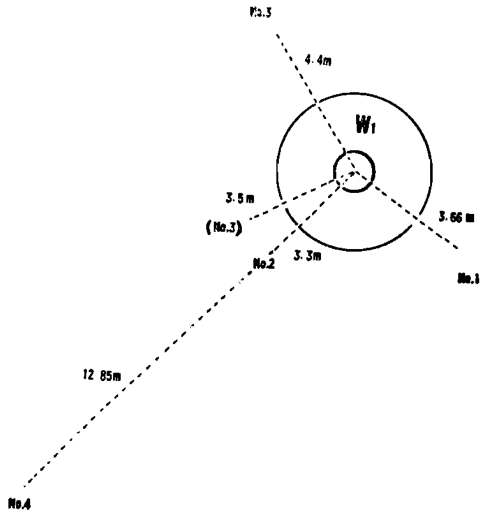


Fig. 10.

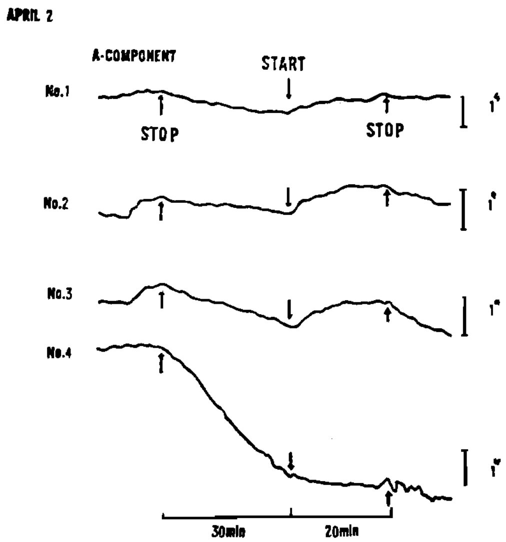
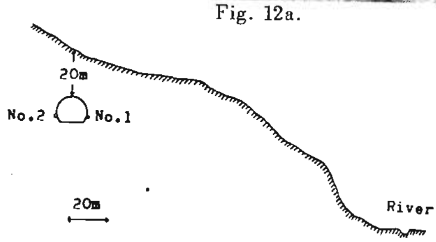


Fig. 11. Tiltgrams obtained at Osaka Gas Company.

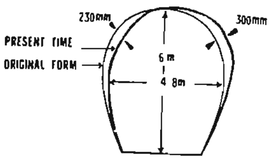
In conclusion, the effect of recharge of water into the well upon the ground deformation near the well, is somewhat in detail observed by P_1-Tiltgraphs. The mode of ground-tilting in both cases of present investigation varies largely from one another, but it can certainly be said that the micro-process and mechanism of ground sinking and rising caused by the change of level of underground water and pressure of underground gas-oil, are possibly clarified to a certain degree by this kind of observation with high sensitive tiltgraph. Moreover, if some simultaneous observations with other instruments such as a high sensitive extensograph are supplementarily applied in the present study with the tiltgraph, a more fruitful result will be expected. Concerning the problem of recharge of water or pressed air for the purpose of prevention of ground-sinking, any definite conclusion or decision can not be gained by the present preliminary observation only, but the question on the temperature and the duration of time in connection with the rate amount of pouring water, will give some good hint for the future development of recharge-problem when good efficiency of hot water in recharge has been observed in the present study.

4. Deformation of Railway Tunnel


Fig. 12a.



A



B

SECULAR DEFORMATION
Fig. 12b.

P_1-Tiltgraph is also effectively used to judge the degree of safety of greatly deformed or cracked railway tunnels, adits of mine, and other underground passages. In this section some views are described of the observational results with a P_1-Tiltgraph designed for the purpose of judging the safeness of a greatly deformed and cracked railway tunnel in the course of repairing construction.

The railway tunnel concerned is an old tunnel of Jōetsu Line in Niigata Prefecture constructed about 20 years ago. (see Fig. 12a)

Its form is as shown in Fig. 12b. It is made of reinforced concrete of 65 cm in thickness and 1200 m in length.

Lately tunnel deformations have become more and more noticeable, and concurrently cracks and water leakage have increased both in number and amount. Really a large amount of secular deformation of tunnel has reached to 30 cm during 20 years since its completion of construction as shown in the lower figure of Fig. 12b. This tunnel is constructed in the underground of 20 m depth of a steep slope of mountain which faces a river as shown in the upper figure of Fig. 12b and the distance between the tunnel and the river is nearly 150 m. The ground formation surrounding the tunnel is highly weathered sandstone, and consequently the ground itself is geologically and topographically liable to cause landslides, faults and cracks. It is considered from the above mentioned conditions that the tunnel is pressed without cease by enormously large lateral earth pressure in the direction to the river by the mountain mass, and resulted in a deformed figure as seen in Fig. 12b.

Under these circumstances repairing was planned to secure safety for train passage.

The repairing was commenced in June, 1955. The process adopted was to reinforce strength of the old tunnel by duplicating the tunnel in wrapping the old one with a new one. Namely a layer of certain thickness of sandy rocks surrounding the outer side of the old tunnel was replaced with a new tunnel wrapping the old one by filling the hollow space with iron frames and concrete. And moreover the construction should be operated without stopping the train traffic. Under these conditions there could necessarily be any convenient observation to watch the safety of the old tunnel in the process of repairing construction, especially in the period of removal of sandy rock around it, and to check the recovery and increase of strength of tunnel after completion of the repair. For these requests a P_1-Tiltgraph was applied for observation of the tunnel deformation during the period of repairing and a certain period after completion.

Two P_1-Tiltgraphs were set up at both sides of the tunnel parts where the deformation was exceedingly large, in the bored cavity 2 m high above the floor at the side wall of tunnel as shown in Fig. 12b. The observation was commenced on July 7, immediately after commencement of the repairing construction and continued for nearly one year. Sensitivity of the instrument was suitably adjusted in the range of 0.5–2.5″/mm, and the rotation speed of photographic recording drum was 1.6 mm/hour. The observation was smoothly operated with no influence of various artificial disturbances such as the ground vibration caused by operation of construction machine and train passing, and the wind pressure caused by train passing as the P_1-Tiltgraphs was critically damped by electromagnetic dampers. Further the meteorological influences such as the rainfall, sunshine, barometric pressures, and change of air and ground-temperature, and the seasonal effects upon the tilting motion of ground at the observation points were also negligibly small, as the observation point was deeply situated more than 20 m below the ground surface and 150 m distant from the entrance of the tunnel.

The obtained results of tilting motion of ground at two points, No.

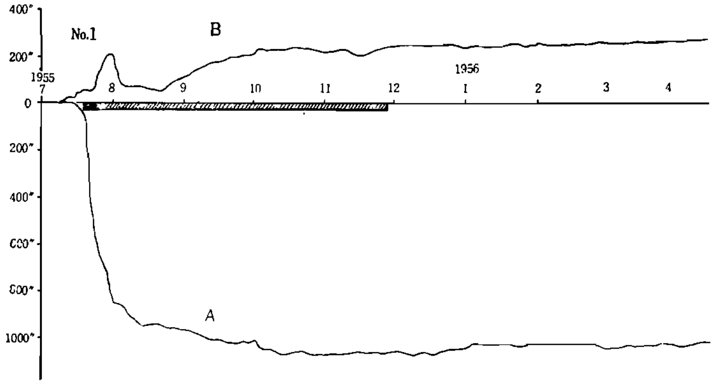


Fig. 13a. Secular tilting-motion observed at station No. 1. The shaded block shows the duration of repairing construction.

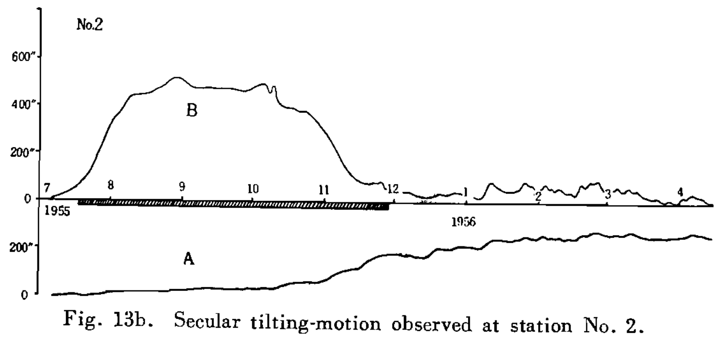


Fig. 13b. Secular tilting-motion observed at station No. 2.

1 and No. 2, are shown in Figs. 13a and 13b. In the Figures, the components A and B of No. 1 and No. 2 show a tilting motion in the direction along and perpendicular to the wall of tunnel respectively, and the upward changes in A and B curves mean tilting motions downward to the direction perpendicular to the paper in Fig. 12b and the river respectively. As is clearly seen in the Figure, the tilting motion at two points No. 1 and No. 2 were relatively calm until July 20. The construction begun in the middle of June, but, in the early stage, the removal of the surface soil was mainly operated, and the operation of removal of sandy stone surrounding the tunnel, considered to influence the tilting motion of tunnel, was only commenced since the middle of July.

Excavation of the sandy rock surrounding the tunnel and filling the hollow space with iron-frame and concrete upon the deformation of tunnel at the observed place are clearly seen in the Figure. Namely effect of excavation during July 20–August 10 is enormously large in amount reaching to several minutes in angle, and then the settlement by filling is also effectively observed during August 10–October 5. The repairing ending on November 25, the newly reinforced tunnel was found to be in a stable state regaining its sufficient strength. The durations of shaded block in Figs. 13a and 13b denote the epoch from the date of commencement of excavation of sandstone surrounding the tunnel to that of finish of whole repairing construction. It is also to be mentioned that minor fluctuations in the tilting motion observed especially at point No. 2 after completion of the construction was caused by many number of small cracks in the tunnel wall originated from wall freezing in winter seasons. In conclusion it was quantitatively and clearly ascertained by the present tiltmetric observation that the present repairing construction of old tunnel was safely and effectively operated for the purpose of reinforcement in strength and increase of safety of the tunnel, in spite of a considerably large amount of deformation of tunnel observed during the process of construction. Really this tiltmetric observation was made in continuation to the end of 1958 by members of the Department of Maintenance of Railway Track, and large deformations in tunnel usually observed before the repairing disappeared after completion of the reconstruction. As seen in the above description the P_1-Tiltgraph proved to be efficiently applied for examination of the strength and stability of underground tunnel, and the check of safeness in process of various construction with regard to the tunnels.

In addition some examples of special tilting motion observed in the process of general survey are presented. Fig. 14 shows an abrupt tilting at No. 1 point caused by the development of a large crack of 10–55 mm in breadth and 50 m in length, running 1 m underneath the point No. 1, when the sandy rocks surrounding the tunnel near the place of No. 1 were removed for reconstruction. But, contrary to the large change at No. 1, the tilting motion observed at No. 2 in case of excavation surrounding sandy rock near the place No. 2 was moderate as seen in Fig. 15 where no remarkable cracks were traced. In both cases the deformation of tunnel was a outward swell of tunnel wall of both sides caused by pressure decrease of the removed sandy rock. Really the tilting motion observed after the filling of con-

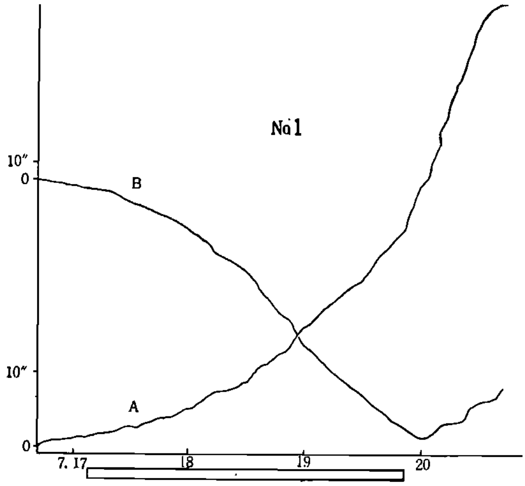


Fig. 14. Abrupt tilting-motion observed at No. 1 during the excavation of surrounding rock. shows the duration of excavation.

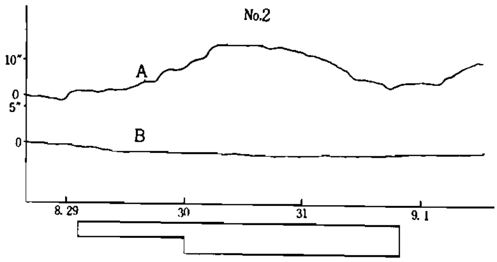


Fig. 15. Tilting-moting observed at No. 2 during excavation of surrounding rock. shows the duration of excavation.

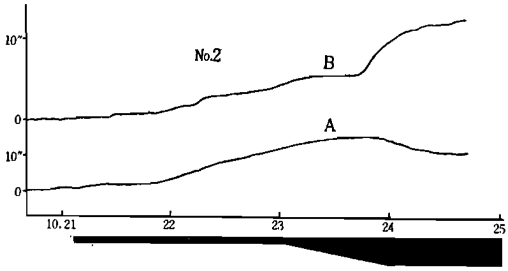


Fig. 16. Tilting-motion observed at No. 2 during the filling of concrete into the hollow space. shows the duration of filling operation.

crete into the excavated space was in reverse of that observed in excavation as seen in Fig. 16. The tunnel deformation was recovered nearly to the original form by these process of excavation of sandy rock and filling of concrete. Next, two examples of tilting motion observed in case of generation of crack are presented in Figs. 17 and 18. In Fig. 17, the change is graphed when a small crack abruptly generated near the point No. 1, and, in Fig. 18, a process of generation of originally hair crack in the tunnel wall beneath the point No. 2, and its development to somewhat large cracks of finally 3 mm in breadth clearly was shown corresponding to the tilting motion of the point No. 2.

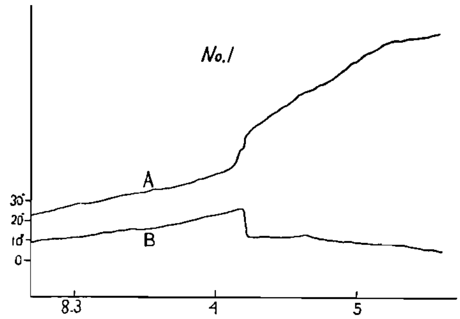


Fig. 17.

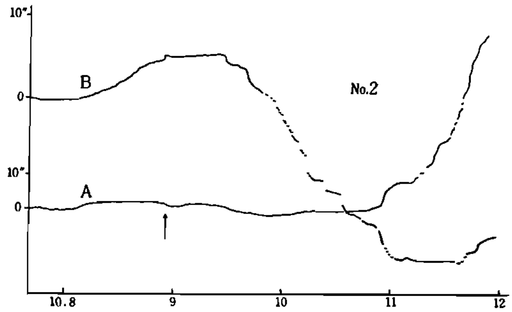


Fig. 18.

In this way, the observation with highly sensitive tiltgraph is profitably operated for study of deformation of tunnel in both processes of long and short interval, and greatly serviceable for preservation of any type of tunnels.

5. Unequal Sinking of Ground and Structure

The problem of unequal sinking of ground and structure is also important in civil and architectural engineering, and counter-plans for them are required. Practically unequal sinking of large amount of structures such as a large and high building, a large dam, a long platform of railway, weir or quay of long and large dimension, the pier of a long bridge, and the recently developed nuclear power reacter of a large scale, and many other structures of large dimension, will give a mortal damage to its keeping and function. Moreover this sort of unequal sinking is also the most dangerous in case of severe earthquakes and other natural disasters because the point of unequal sinking is usually the most frail part of the structure.

Under these circumstances, the problem of unequal sinking of ground and structure is eagerly researched in many aspects of it, and the levelling survey is ordinarily applied to this subject. In usual cases a change in the height difference of two points in a certain interval of several days or months is obtained by frequent operations of levelling survey, but the micro-process of sinking and micro-behavior of ground and structure are not definitely observed by this sort of levelling survey. The result is reported in the present section of the continuous observation with 4 sets of tiltgraph at the building of Osaka Railway Station during one year from December, 1954 to December, 1955 to study the micro-process of unequal sinking of the Station Building.

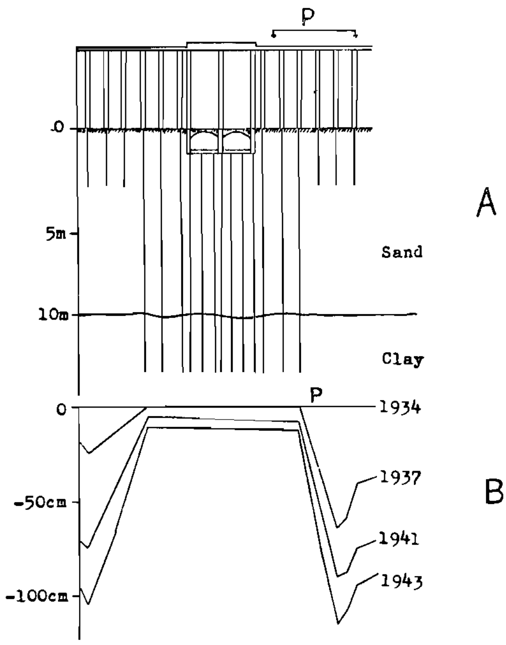


Fig. 19.
A : Sectional distribution of foundation pile
B : Amounts of sinking in each year

Unequal sinking of the platform and building of Osaka Railway Station have been increasing since its establishment in 1934, as shown in Fig. 19. The cause of unequal sinking in the present case is mainly in the difference of length of foundation piles which are 5 m and 15 m respectively as seen in the Figure. The short pile is driven into a somewhat weak sand layer, and the long one into a little stiff clay layer as shown in the Figure. By this difference in amount of sinking of the foundation piles, the platform and the building of Osaka Railway Station have been suffering a great damage of unequal sinking, especially at the joint point of the two different piles. The amount of sinking during 10 years after the establishment in 1934 was measured as shown in the lower figure in Fig. 19, reaching a surprisingly large amount of 100 cm in 10 years, and its effect is clearly seen in the photograph in Fig. 20.

Four sets of P_1-Tiltgraph were set up at 4 points where the unequal sinking is the most conspicuous to study in detail the nature and behavior of sinking by simultaneous and continuous observation. The positions of tiltgraphs of No. 1, 3 and 4 are shown in Fig. 21, No. 1, No. 3 and No. 4 being placed at the basement floor, the middle floor (the middle floor between the basement and platform), and on the platform, respectively. And No. 2 was frequently moved to same places of comparatively small sinking for comparison with other tiltgraphs of No. 1, 3 and 4. The observation period extended from December 1954 to December

Fig. 20. Photograph of a part of Osaka Station. P corresponds to P in Fig. 19.

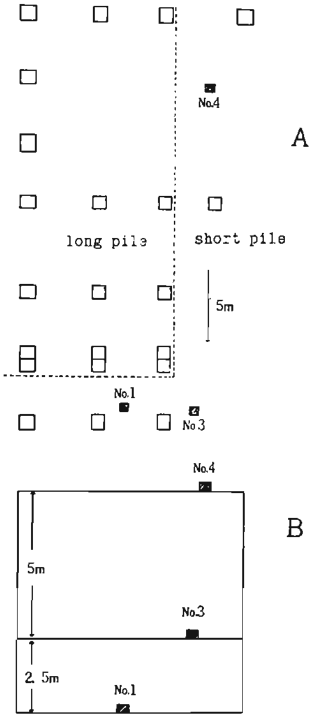


Fig. 21. Arrangement of P_1-tiltgraphs.
A : its plane
B : its elevation

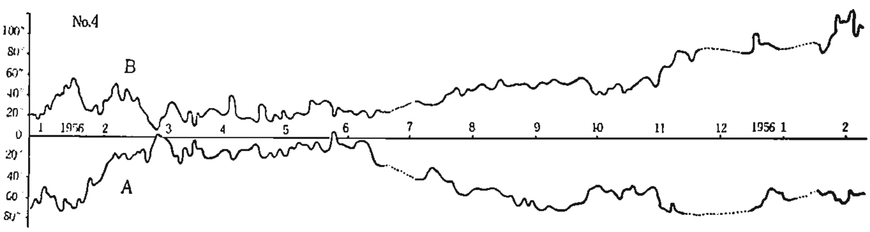


Fig. 22. Secular tilting-motion observed at No. 4.

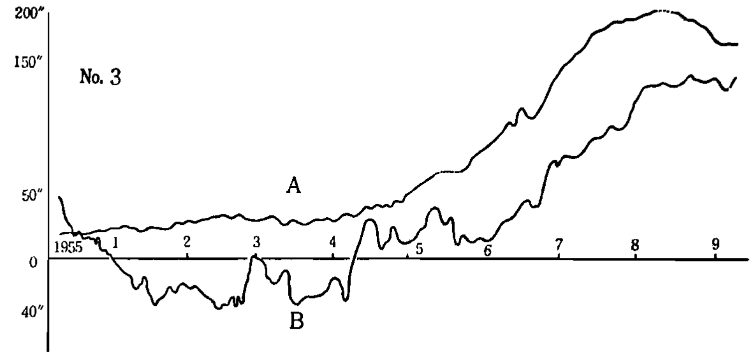


Fig. 23. Secular tilting-motion observed at No. 3.

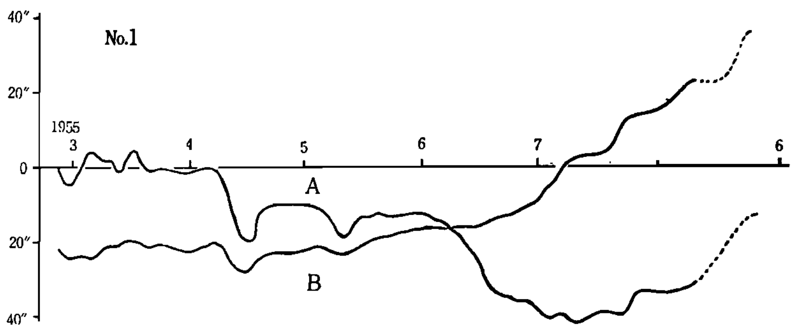


Fig. 24. Secular tilting-motion observed at No. 1.

1955, and the observed tilting motions at 3 points of No. 1, 3 and 4 were, as graphically, shown in Figs. 22, 23 and 24 respectively. It is to be mentioned here that the curves in the three figures are presented after averaging the daily variation of tilting motion which is mainly affected by the so-called "buckling motion" of structure caused by meteorological change.

Concerning the results graphed in the three figures, all curves are considered to show, in general aspect, a summation of secular tilting motion caused by ground sinking and annual variation of tilting motion originated from the seasonal variation of temperature, sunshine, precipitation, level of ground water and others. Their ranges of variation are nearly 70″, and 250″, and 130″, at the points No. 1, No. 3 and No. 4 respectively. Among them the amount observed at the point No. 3 is unusually large, and there the secular variation is estimated to reach more than 150″. Really the place of No. 3 is that of the most intense sinking and the stairs on which No. 3 was set up have been frequently reconstructed to restore to normality. With regard to the secular variation at No. 4 point, its amount is estimated nearly as 25″ which is deduced by subtraction of annual variation from the observed result. In the way the estimated amount and direction of secular tilting motion at three points of No. 1, 3 and 4 are shown in Fig. 25. These figures correspond to the behavior of tilting motion during one year at three points brought about by unequal sinking of ground and structure.

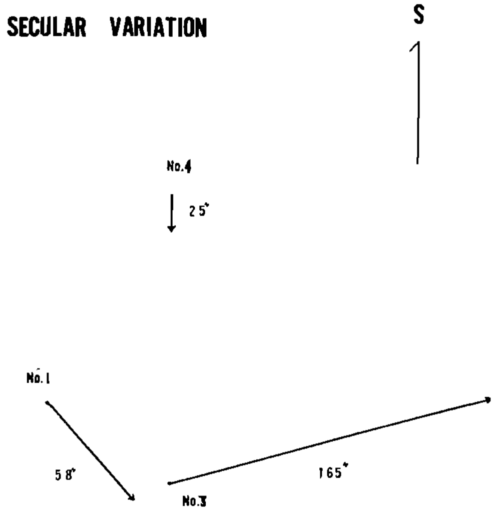


Fig. 25. Total amounts and diretions of secular tilting-motion obtained at three observation points of No. 1, 3 and 4.

Next, examining in detail the curves in Figs. 22, 23 and 24, somewhat irregular fluctuations are frequently observed, especially in the period from March to June, and really these anomalous disturbed motions are commonly observed at three points as shown in Fig. 26. In spite of the divergence of their direction and amount, the time of occurrence of these disturbances is in good accordance for each point.

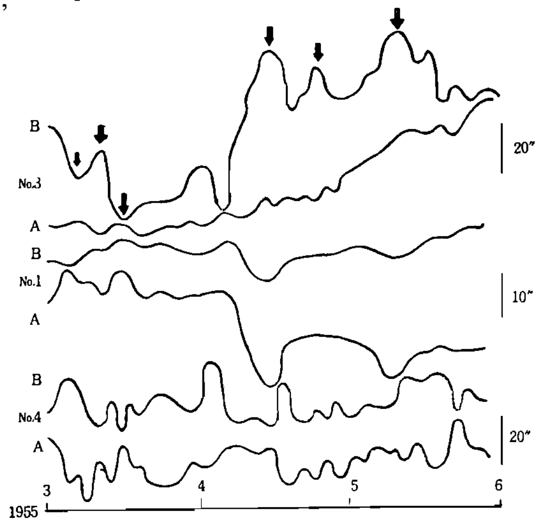


Fig. 26. Tilting-motion commonly observed at three points of No. 1, 3 and 4.

These disturbances are explained as excited mainly by sudden changes of air and ground

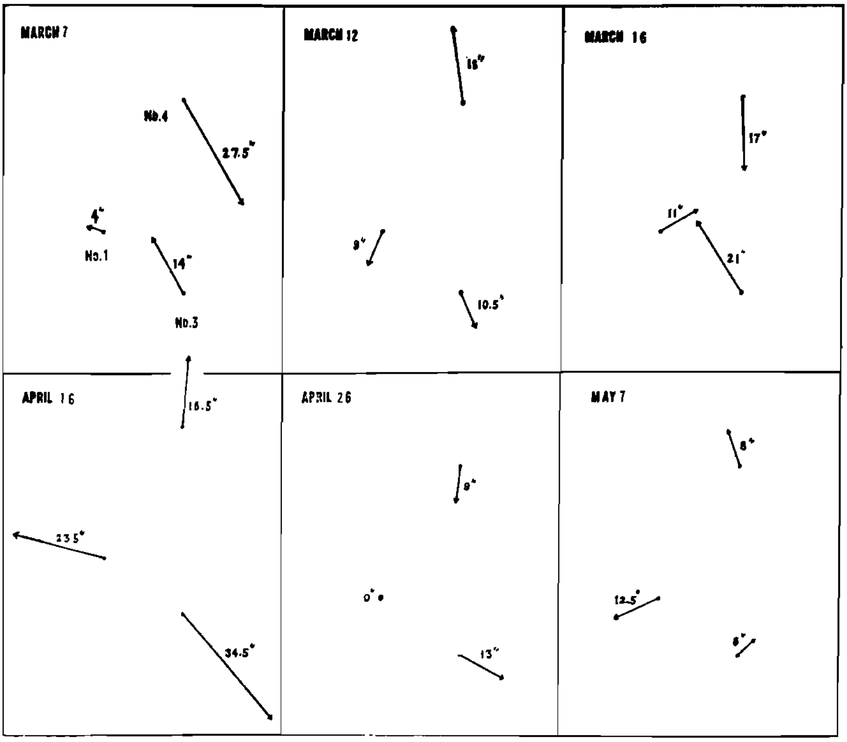


Fig. 27. Some examples of disturbed tilting-motion commonly observed at three points of No. 1, 3 and 4.

temperature, heavy rainfall, sudden level change of underground water, and some examples of disturbed tilting motion are shown in Fig. 27. In the Figure, two cases of March 12 and April 16 are clearly explained by the sudden rise-up of room temperature observed in the amount of 6°C and 12°C respectively. But, in other four cases of March 7, March 16, April 26 and May 7 in the Figure, no influential changes of meteorological origin or level of underground water recorded at two wells near the station, are not observed, and consequently these observed disturbances concerned remain unexplained.

On the daily tilting motion observed at three points, their mean amplitudes are nearly $2''$-$6''$, $4''$-$10''$ and $8''$-$15''$ at the points No. 1, No. 3 and No. 4 respectively. It is simply said that the amplitude of daily tilting motion, in the present case, increases as the story rises higher. But, in detail examining, the mode and amplitude of each daily variation at three points are divergently different with each other, and, moreover, are greatly influenced by climatic and seasonal conditions.

In conclusion, the secular sinking of structure of Osaka Railway Station, especially the mode of unequal sinking was studied by continuous observations with 4 sets of tiltgraph during one year. Each secular tilting motion at 3 points observed is nearly consistent, both in the mode and amplitude, with the result obtained by operation of levelling survey during 1954–1955. In the present observation it was found that the mode and amplitude of annual and daily variation of tilting motion were surprisingly divergent from point to point in such a large and long structure as the present station building. This diversity was presumably caused by, in the present case, irregularity in foundation piles and complexity of the structural composition with various types of platform, underground compartment, and many wide stairs everywhere in the building. Moreover the problem of sudden and complicated disturbances commonly observed at every point was very interesting and suggestive for solving the nature of irregular sinking of every part in the building, but remains unexplained at the present stage. In final, it was with certainty concluded from results of the present preliminary observation that the complex nature of unequal sinking of the large structure would be solved by precise observations at every part in the structure with the highly sensitive tiltgraph supplemented by simultaneous observations of temperature in air, ground and building block, and the level change of underground water near the building and structure.

6. Deformation of Dam

Recently dam constructions are increasing for hydroelectric power, irigation, flood regulation, and or their combined effects. There are many kinds of type of dam which are classified in its form, shape, and the constitutional material, and gravity-, earth-, rock fill-, arch-, and hollow-dam are names usually adopted. In all cases, especially of a long and high dam of large scale, the pressures of dam itself upon the foundation rock, and of water in full load in the dam, and the stress generated in the dam by oscillatory water of dam in case of strong earthquake, are all considered to be enormously large. Consequently the security for safety and stability of a dam is first of all necessary in construction and keeping of dam to prevent disasterous damages that a dam breaking will cause. Hence a deformation of dam and foundation rock must be continually kept under observation during the construction and in keeping of a dam. As part of that several sets of tiltgraph and strain-guages are applied to some dams of different types for observation of deformation of the dam itself and foundation rocks, and some results are here reported as under.

(a) Case of Test Arch Dam at Sudagai

In the present case, a small arch dam of Sudagai on upper reaches of River Tone in Gunma Prefecture which was constructed for test of strength, has been observed by 2 sets of tiltgraph for examining the mode and amplitude of deformation of foundation rock in case of full load of water in the dam pool. The main arch dam of reinforced concrete is 77 m in height, 200 m in length and 65 m in base-breadth, but the present small arch dam of reinforced concrete for test is 12.8 m in height, 0.6 m in mean breadth, 23.0 m in radius of curvature, and 140° in the central angle, as shown in Fig. 28. In the present experiment the deformation of foundation rock was observed at 4 points of A, B, C and D in case of full load of water in the pool amounting to nearly 47,000 m^3 and keeping 4 hours in duration. The geological formation of foundation was mainly granite mixed partly with sandy conglomerate, and the period of observation being December 2-10, 1953.

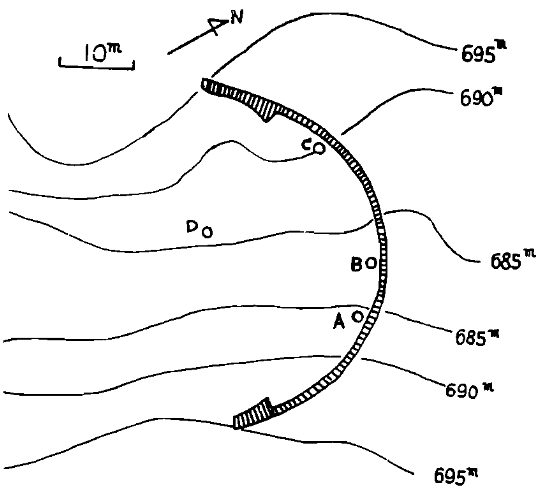


Fig. 28.

In the course of observation, filling and discharge of water in the pool were operated several times to study the tilting motion of foundation rock nearby the dam at 4 points generated by such operations. In the present observation, the daily variation of tilting motion of ground caused by meteorological element was not observed at all points where daily variation of atmospheric temperature was in the range of nearly 3°C.

Mode and amplitude of ground deformation observed at 4 points generated by the effect of water load, were considerably divergent, but here the result obtained at the point A, where the observation had been good compared with at other points, would be presented.

As an example, the tilting motion of ground at the point A observed in case of trial operation of filling (charge) and discharge of pool water on December 12-13 is shown in a vector diagram in Fig. 29. In the Figure, the vectors in the directions of axes of U- and L-side mean a downward tilting in the direction of upper course of river and that of left side of dam respectively. As seen in the Figure, the ground at A commenced the tilting motion in the direction of upper course of the river immediately after the beginning (13 h 10 m, Dec. 12) of filling water operation, and then, combining with the tilting motion in the direction of left-side of the dam, the maximum tilt reaching the amount of 2.9″ in U-direction and 1.3″ in L-side direction respectively in time (16 h 40 m) of full load of water (10 m in height). Coinciding with the beginning of discharge operation of water, a tilting motion is reversed in the direction of the lower course of the river and, in time (8 h 00 m, Dec. 13) of full discharge of water, the component of tilting motion in the direction of river returns almost to the original state. But the component or-

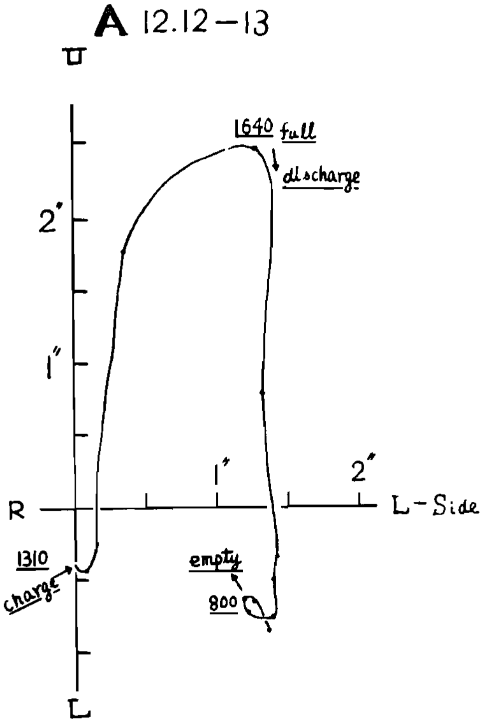


Fig. 29.

thogonal to the river has shown a remaining, permanent set of ground-tilt in the direction of the left side of dam amounting to 1.2″ in the present case. It is to be remained that the attraction of water working upon the tiltgraph has been ascertained to be negligible in the present case. Next, the same data are plotted in Fig. 30, as indicating a relation between the amount of tilting motion (θ in abscissa) and the height of water level in the pool (W.L. in ordinate). In the Figure, the curves of (U-L) and (R-L side) show behaviors of the ground-tilt in the radial and tangential components to the arch of dam, the radial direction at A being deviating 20° from the line of river. As clearly seen in the Figure, it shows a nearly complete return to the original state in the radial component, but a considerable amount of residual tilt with a character of permanent set is also observed in the tangential component. Concerning this sort of residual ground-tilt, these permanent sets of tilt have been observed in a considerable amount in both radial and tangential directions in the first operation of filling and discharge of water in the pool, but becoming smaller and smaller in accordance with the number of repetition of operation and finally negligibly small after several operations in the radial component. Contrary to the radial component, the tangential components are in every time, subject to the permanent set of tilt of considerably large amount in spite of repetition of operation several times. This fact of generation of remaining permanent set of ground-tilt toward left side of the dam must be watched of the dam concerned for its safety and stability for

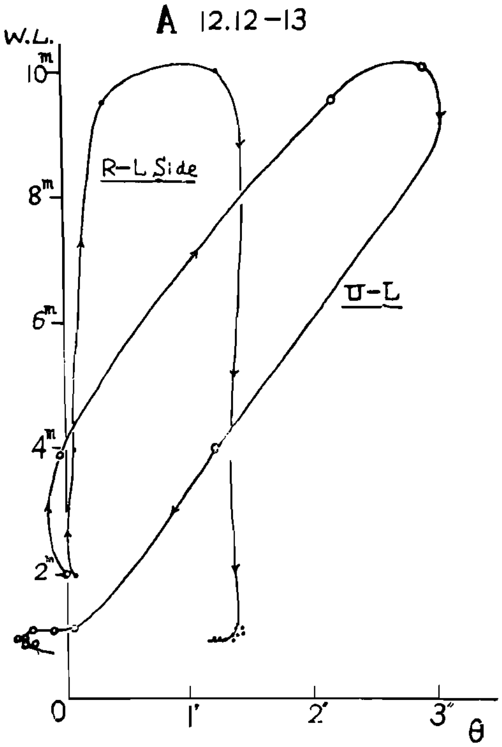


Fig. 30.

any emergency. In the present case, this peculiar, permanent set of tilting is presumably explained by an unequal distribution of maintenance-strength in foundation rock where a weak layer of sandy conglomerate is embeded everywhere in the foundation rock of granite in left side of the dam.

In the present observation with tiltgraph at the small arch dam for testing, some peculiar ground deformations caused by water load in the pool are observed. The present observation has a preliminary and reconnoitring character to judge the applicability and profitableness of tiltmetric observation for the study of safety and stability of the dam, and its propiety is considered to have been proved to a certain degree by the present observation. In the following paragraph, the results of observation with tiltgraph and strain-gauge made in somewhat detail at two dams will be described.

(b) Case of Gravity Dam at Miyagawa

The Miyagawa Gravity Dam is situated at the upper stream of River Miya in Mie Prefecture. Its height, length and volume are 88.5 m, 225 m and 380,000 m^3 respectively of which construction was initiated in 1953 and completed in December, 1956. The foundation rock is tight diabase, and no remarkable fault is found around the dam foundation. The capacity of impounding reservoir (pool) is about 64,000,000 m^3, and the traverse and longitudinal sections are respectively represented in Figs. 31a and 31b.

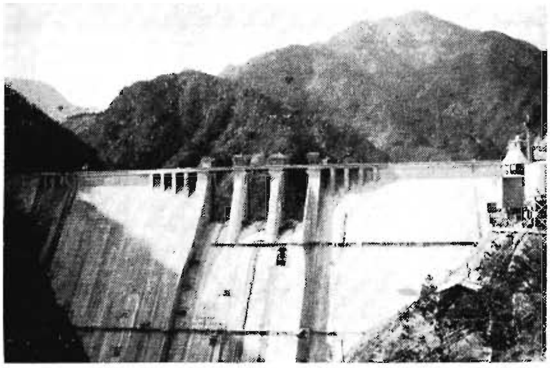


Fig. 31a. Photograph of Miyagawa Dam.

In the present case, 4 sets of P_1-Tiltgraph and extensograph of Benioff's bow-string type have been operated to study the micro-process of dam-deformation caused by filling the pool with water. In this article, the results obtained by P_1-Tiltgraph only are reported. Tiltgraphs set up at 4 points at P_1, P_2, P_4 and P_5 in the inspection gallery of the dam,

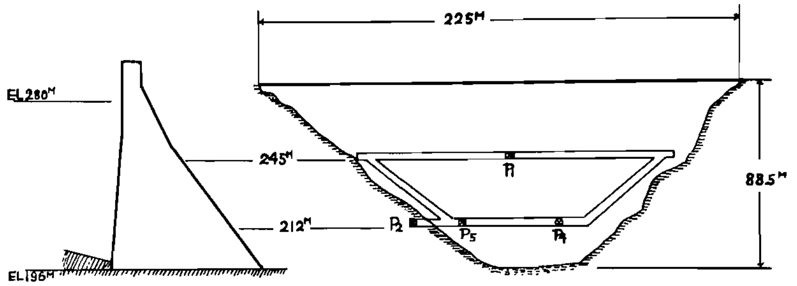


Fig. 31b. Sectional representation .of Miyagawa Dam.

are shown in Fig. 31b. For the purpose of studying accurately the dam-deformation effected by water load in the pool, the ordinary dam-deformation caused by the internal stress of dam itself, the deformation of foundation rock, the thermal stress originating in the temperature change of pool-water, air, and concrete effected by meteorological change of sunshine, rainfall and others, have previously been investigated. Along this request the observation started during the construction in September, 1956, and it was continued until May, 1957 after the first filling of water in the pool on December 14, 1956.

Observational results obtained are as follows : The daily variation

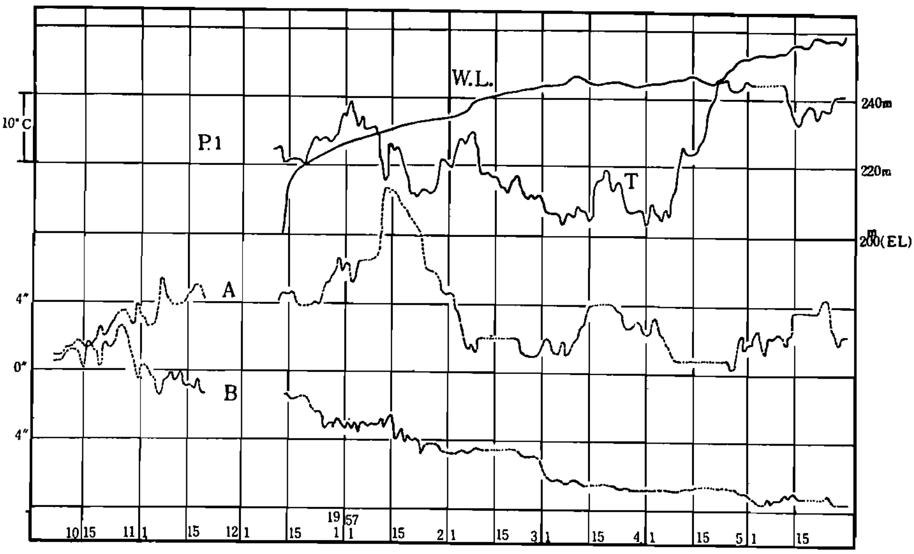


Fig. 32. Secular tilting-motion observed at P_1.
A, B : Tilting T : room temperature W.L. : water level

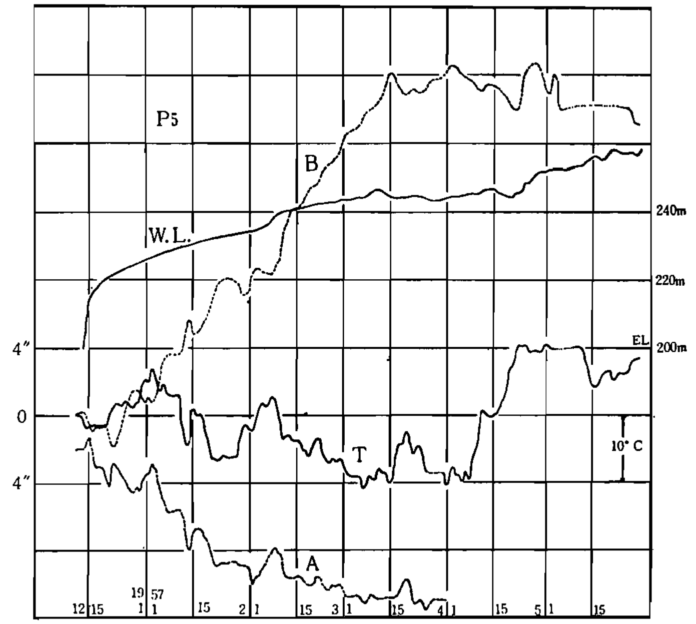


Fig. 33. Secular tilting-motion observed at P_5.

of tilting motion, caused by the buckling motion of dam of thermal origin, is more or less observed at several points in the inspection gallery. Its double amplitude in maximum is 2″ at P_4 and less than 1″ at other 3 points. The secular tilting motions observed at 4 points are represented in Figs. 32, 33, 34 and 35 in which the daily variation is eliminated. In each Figure, the curves of A, B, T and W.L. denote the tilting motion in the longitudinal and transversal direction of river, the room temperature in the inspection gallery, and the water level in the pool respectively. It is regretable that, in spite of our endeavor, the complete observation before the epoch of filling water in the pool (December 14, 1956) was only operated at point P_1, and the observations at other 3 points were initiated at the some epoch with commencement

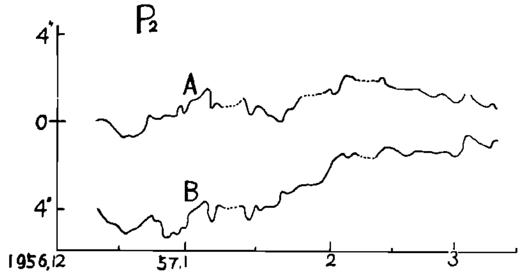


Fig. 34. Secular tilting-motion observed at P_2

of the filling.

The effect of water filling upon the tilting motion at 4 points is represented in a vector diagram of tilt in Fig. 36. As shown in the Figure, the point P_1 which is situated at the central point of upper part of dam tilted first downward in the direction of lower stream in accordance with the commencement of filling water in the pool on December 14, 1956 and then, after one month, it reversed its tilting motion to the upper stream, and finally remained in a permanent tilt of 5″ at the epoch of end of observation in May, 1957. At the point P_4 and P_5 which are both situated at the lower part of dam and near the foundation rock of left and right bank respectively, the tilting motion after the commencement of filling is mainly towards the direction of their own banks, reaching 10″ and 20″ in their final amounts,

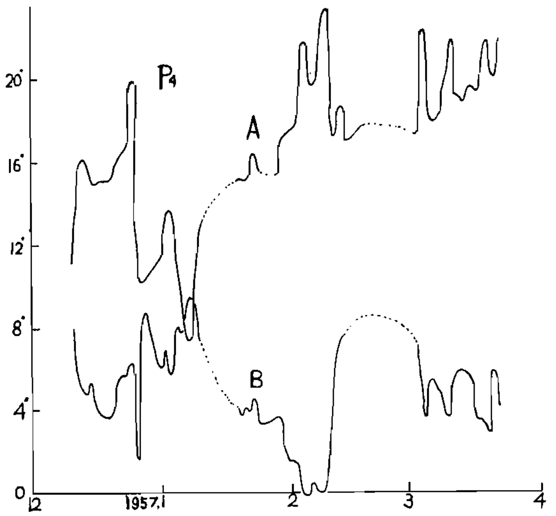


Fig. 35. Secular tilting-motion observed at P_4.

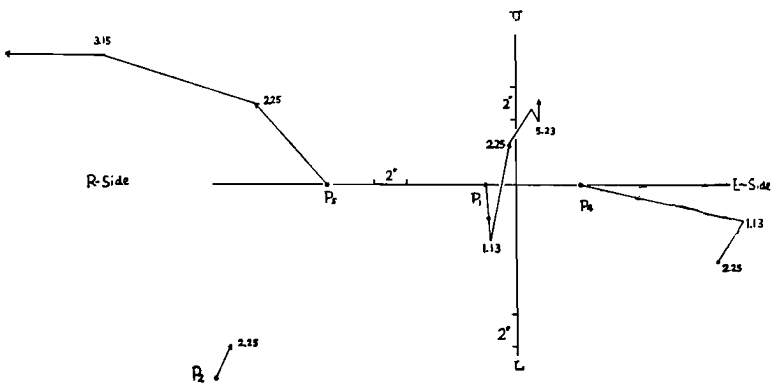


Fig. 36. Vectorial representation of tilting-motion at four points of P_1, P_2, P_4 and P_5 as affected by water filling in the pool.

as in the Figure. With regard to the point P_2 situated at the end room of crossinspection gallery in the lower part of the dam, its position being just in the foundation rock of the right bank, the effect of water filling upon the point P_2 is the tilting motion towards the direction of upper stream in amount of $2''$ which is interpreted as pure deformation of foundation rock caused by the water load in the pool. Next, for the sake of reference, two graphs of Figs. 37 and 38 are represented to show

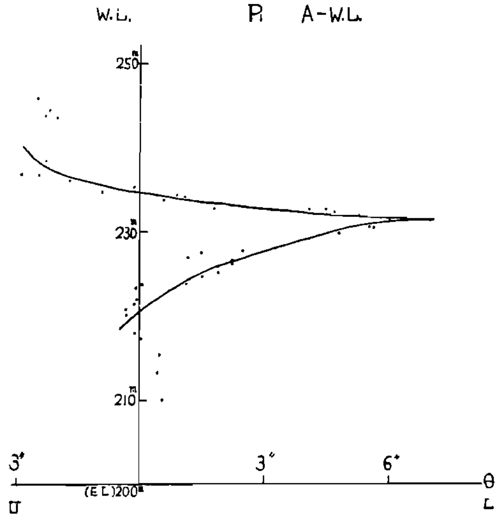


Fig. 37.

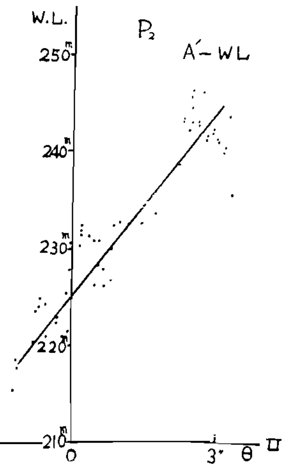


Fig. 38.

the relation between the tilting motion in the longitudinal direction of stream affected by the water filling in the pool and the water level of the pool. In Fig. 37, the tilting motion observed at P_1 shows a strange reversed motion at the water level of 235 m as already mentioned. This phenomenon of anomalous inversion is very interesting and suggestive, but its real cause can not yet be explained. Concerning Fig. 38, the tilting motion caused by the water filling at P_2 in the foundation rock of right bank is, in general, toward the direction of the upper stream, their amounts being linearly proportional to the water level of the pool. But, in detail, the fluctuating character of tilting motion, as seen in the Figure, is an interesting fact and will be serviceable in future for study on behavior of foundation rock of dam deformed by the water load in the pool.

In conclusion, the tilting motion caused by the filling water in the dam-pool was observed at 4 points in the inspection gellery of Miyagawa Gravity Dam. In the present case, the central, upper part of dam showed a complex tilting motion in the longitudinal direction of river, and the lower part of the dam near the bank, a large tilting motion towards the direction of their respective bank. The foundation rock also showed a small tilting towards the direction of upper stream in case of filling. Thus, the deformation of a dam and its foundation rock caused by the water load in the dam-pool could in detail be investigated by precise tiltmetric observations at several points in the dam and foundation rock.

In addition, an example of ground-tilting observed at P_1 caused by a sudden, severe rainfall was presented. In the dam-area, a severe rainfall in the night of October 19, 1956 and the water level in the pool rising to 20 m in one day. In the usual course of water-filling in the pool which was initiated on December 14, 1956, the averaged rate of level-rise was 0.5 m per day. Contrary to this small rise of level in normal course of filling, that rise of 20 m in one day was exceedingly large, and presented a valuable example. The tilting motion observed at P_1 in the present case was

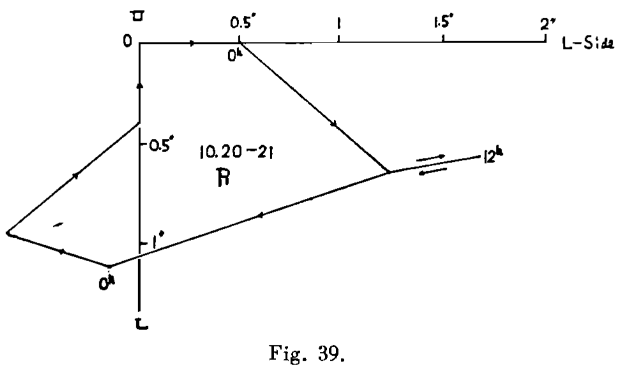


Fig. 39.

vectorially shown in Fig. 39. Namely the tilting motion caused by the heavy rainfall was first towards the direction of the lower stream in the amount of $1''$ and of left bank in $1.7''$, and then reversed its direction to that of right bank, completing its cycle of motion in 2 days after beginning of the rainfall. This kind of observation in micro-process of dam-deformation caused by a rapid change of water level in the pool was also useful for the study on the degree of safety and stability of dam for external, violent disturbances such as the strong rainfall, the earthquake, the crack formation in dam and foundation rock and the like.

(c) Case of Nagase Dam

Nagase Dam is a gravity dam in the upper stream of River Monobe in Kōchi Prefecture. Its hight and top length are 85 m and 180 m respectively as seen in Figs. 40a and 40b. It was already completed in construction and filled with water in the pool in the epoch of the present observation initi-

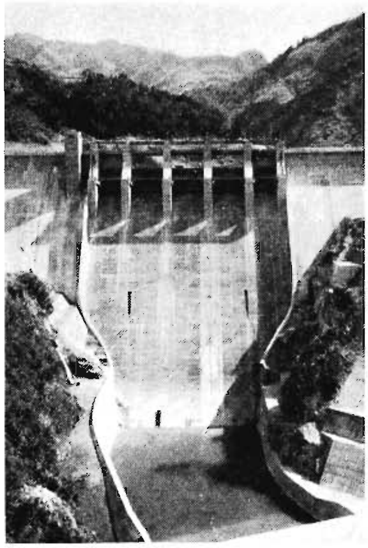


Fig. 40a. Photograph of Nagase Dam.

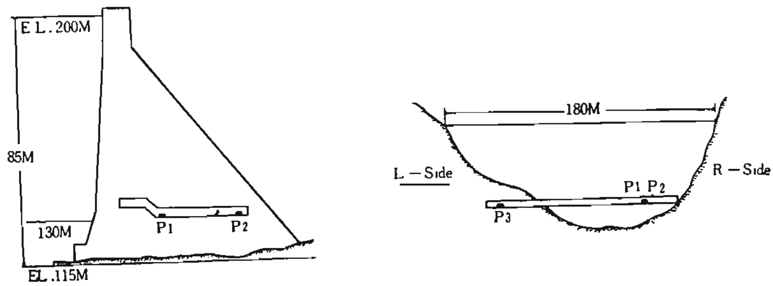


Fig. 40b. Sectional representation of Nagase Dam.

ated on March 23, 1957. The geological formation of foundation rock is sedimentary, with complex mixing of sandstone, sandy shale, shale and conglomerate. The 3 P_1-Tiltgraphs and extensographs of Benioff's bowstring type were set up at 3 points P_1, P_2 and P_3

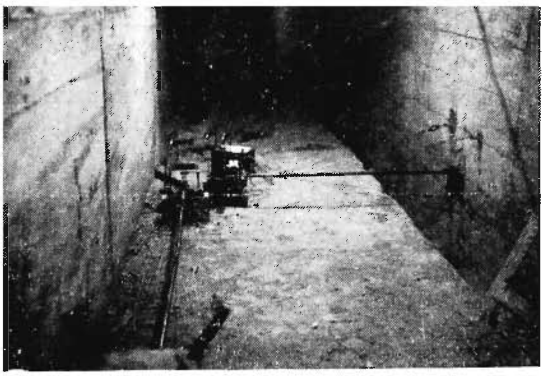


Fig. 40c. Observation point in the inspection gallery.

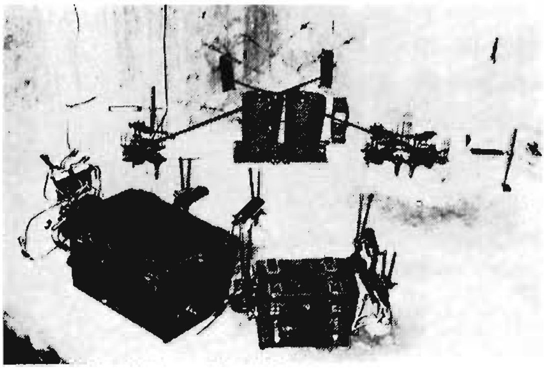


Fig. 40d. Photographs of tiltgraph and extensograph set up in the inspection gallery.

in the inspection gallery as shown in Figs. 40b, 40c and 40d, to study the deformation of dam and foundation rock caused by the change of water load in the pool. The observation initiated on March 23, 1957 was continued until the end of 1959, but in the present article, the results obtained with P_1-Tiltgraph during the period of March-August, 1957 would preliminarily be reported.

In the period of observation concerned, some examples of change of water-level in the pool caused by rainfall and the daily change of water-level by the regular operation twice a day of charge and discharge of pool-water for the purpose of generation of electric power, will be men-

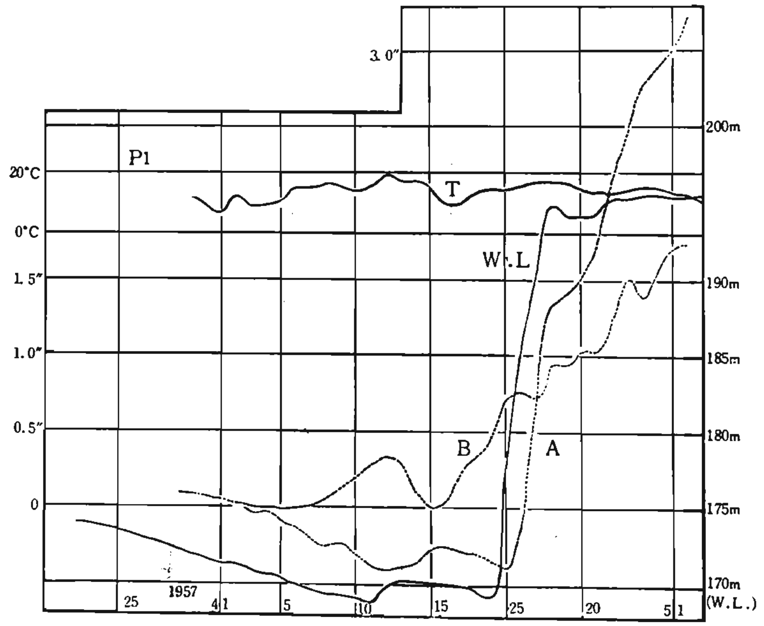


Fig. 41.

tioned in connection with the tilting motion at 3 points. One is an example of long, heavy rainfall with 6 day's duration from April 18 to 23 whose total amount of precipitation reaching 340 mm, and the water-level in the pool raised to 23.75 m in a few days. Another is a small rainfall on April 10–11 with precipitation of 44 mm which resulted in the rise of 1.54 m of water level in the pool. And, a gradual fall of water level with the averaged rate of 25 cm per day during the initial epoch of observation was also noted, as all represented in Figs. 41 and 42 in accordance with the tilting motion at point P_1.

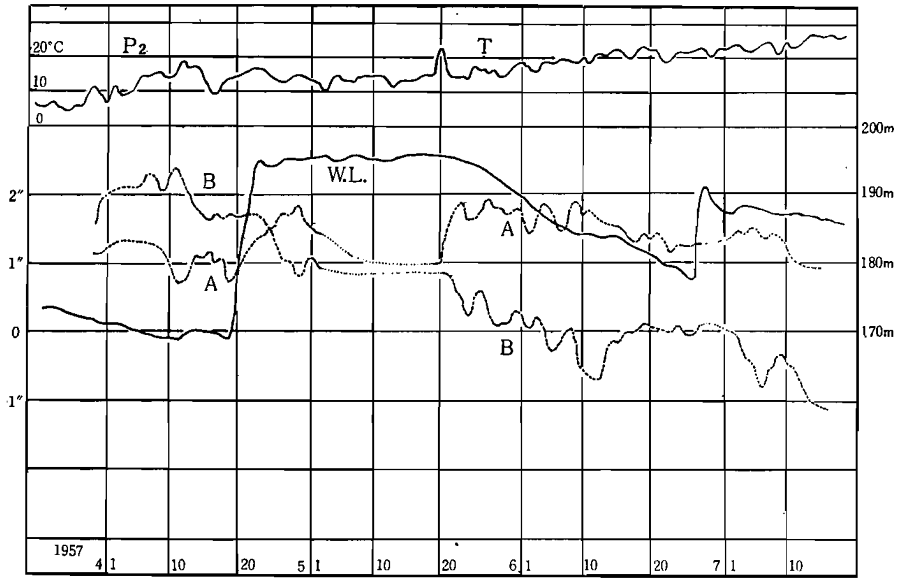


Fig. 42.

Concerning the tilting motion observed at P_1, the A-component which shows tilting motion in the longitudinal direction of river is in perfect accordance with the change of water load in the pool as clearly seen in Figs. 41 and 42. Namely the A-component has been tilting towards the direction of the upper stream in a rate of 0.036″ per day, in correspondence with the fall of water level in rate of 25 cm per day during the period of March 29–May 11. Next, it tilted reversely in the direction of lower streams in amount of 0.025″ by the effect of a small rainfall on April 11 which raised the water level to 25 cm. It should also be remarked that the commencement time of tilting motion was one day behind the rise of water level. A long and heavy rainfall of 6 day's duration occurred on May 19, when the water level in the pool rose rapidly to 25.75 m, and in this case, the A-component also showed a violent inclination in the direction of the lower stream, but its rate was 0.016″ per 25 cm-level change somewhat small compared with other cases. Also in this case, the commencement of tilting motion was one day behind the beginning of water-level rise. Concerning the B-component which denotes the tilting motion in the transversal direction of river, its motion has shown a secular tilt downwards the dirction of right bank with ir-

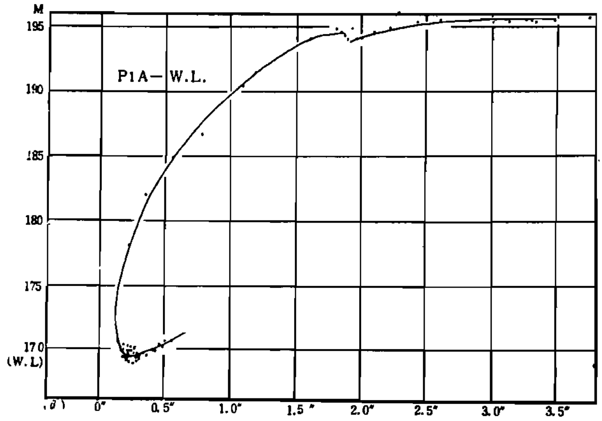


Fig. 43.

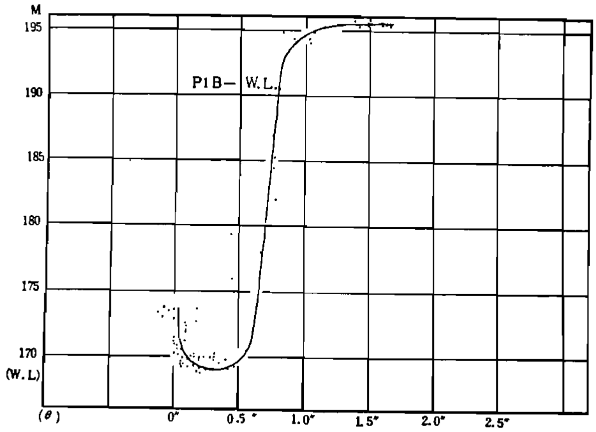


Fig. 44.

regular fluctuations, the total amount of tilt reaching 3″ during the observational period from April to August.

Next, Figs. 43, 44 and 45, are represented the correlation between the water-level in the pool and the amount of tilting motion observed at the point P_1 in the component of A and B, and the point P_2 in the component of A (same direction with that of A-component at P_1).

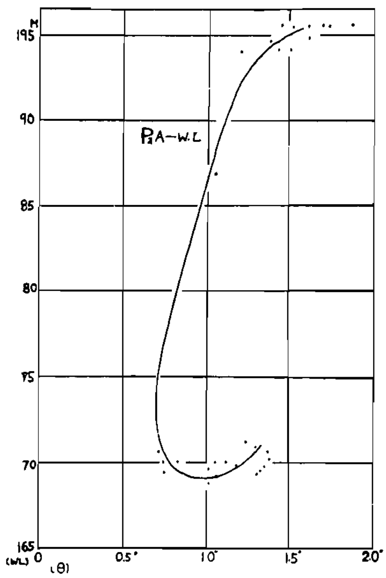


Fig. 45.

Concerning the regular change of water-level by discharge and charge of pool-water twice a day for generation of electric power, an example is presented in Fig. 46. In the Figure, the graphs of water-level, and tilting motion in the longitudinal direction of river observed at the point P_1 are plotted in full line. Namely, in spite of operation twice a day, the curve of water-level shows a diurnal variation in the Figure, because the measurement of level height of pool-water is practically made twice a day at 9 h and 21 h. And, on the other hand, the curve of tilting observed is really semidiurnal. From the reason, the curve of dotted line is conventionally plotted connecting the values at 9 h and 21 h for the sake of comparison of tilting motion with a change of water-level. In this way, one to one correspondence of daily tilting motion with a daily change of water-level is clearly observed to show that rise and fall of water-level cause the tilting motion of dam in the direction of lower and upper stream respectively. The amount of tilting also in this case nears 0.017″/25 cm-water-level change which is in the

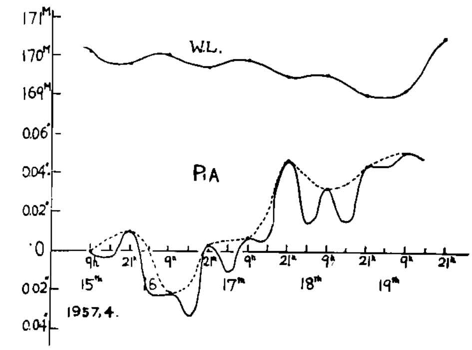


Fig. 46.

same order of magnitude as in other disturbances of rainfall.

In concluding the section 6, some matters must be mentioned. In the present case, the deformation of dam and foundation rock, caused by the change of water-load in the pool of dam is somewhat in detail observed at three dams with several sets of P_1-Tiltgraph and extensograph. In every case the behavior of dam and foundation rock affected by the change of water-level in the pool is observed to be unexpectedly complex, and it is found that every part of dam-structure is deformed in a considerably different mode from each other. From these results it is certainly said that this kind of observation should necessarily be operated to examine the safety and stability of dam-structure and the degree of adhesion between the dam and foundation rock. And this kind of observation with many sets of tiltgraph and extensograph at every point in the dam and foundation rock is considered to be securely serviceable for prevention of disasters by collapse of dam and others.

7. Summary and Acknowledgement

In conclusion of the present article, some considerations will be presented. As a new method of investigation the micro-process of deformation of ground and structure caused by various external, disturbing forces, the precise observation with a highly sensitive tiltgraph and extensograph is applied to some cases of such phenomena as deformation of ground caused by level-change of the underground water, the deformation of railway tunnel caused by earth pressure of surrounding rock, the unequal sinking of structure caused by unequal distribution in length of foundation pile, and the deformation of dam caused by change of water load in the pool. It is concluded, as a whole, that the mode of deformation of ground and structure affected by disturbing force or stress is unexpectedly complicated, and a simultaneous observation with a small set of instrument of such kind as tiltgraph, extensograph, vibrograph and allied instruments, at every point of the structure concerned, is highly recommended to check and confirm the security of structure and structure-maintenance.

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